Thermal seawater desalination for irrigation purposes in a water-stressed region
Emerging value tensions in full-scale implementation

Gamboa, Gonzalo; Palenzuela, Patricia; Ktori, Rodoula; Alarcón-Padilla, Diego C.; Zaragoza, Guillermo; Fayad, Samar; Xevgenos, Dimitros; Palmeros Parada, Mar

DOI
10.1016/j.desal.2024.118213

Publication date
2024

Document Version
Final published version

Published in
Desalination

Citation (APA)
Gamboa, G., Palenzuela, P., Ktori, R., Alarcón-Padilla, D. C., Zaragoza, G., Fayad, S., Xevgenos, D., & Palmeros Parada, M. (2024). Thermal seawater desalination for irrigation purposes in a water-stressed region: Emerging value tensions in full-scale implementation. *Desalination*, *593*, Article 118213. https://doi.org/10.1016/j.desal.2024.118213

Desalination 593 (2025) 118213

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Thermal seawater desalination for irrigation purposes in a water-stressed region: Emerging value tensions in full-scale implementation

Gonzalo Gamboa [a,*], Patricia Palenzuela [b,d], Rodoula Ktori [c], Diego C. Alarcón-Padilla [b,d], Guillermo Zaragoza [b,d], Samar Fayad [d], Dimitros Xevgenos [c], Mar Palmeros Parada [e]

[a] Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona, Barcelona, Spain
[b] CIEMAT-Plataforma Solar de Almería, Almería, Spain
[c] Faculty of Applied Science, Technical University of Delft, Delft, the Netherlands
[d] Centro mixto CIESOL, Universidad de Almería, Almería, Spain
[e] Faculty of Civil Engineering and Geosciences, Technical University of Delft, Delft, the Netherlands.

HIGHLIGHTS

- Thermal technologies allow achieving zero liquid discharge in seawater desalination
- Zero liquid discharge entails larger land use inland
- Thermal desalination shows lower CO_2 emissions per cubic meter of desalinated water
- Thermal desalination inland shows larger costs due to seawater transport and equipment
- Recovering resources from brine increases economic viability of thermal desalination

ARTICLE INFO

Keywords:
Thermal seawater desalination
Responsible Innovation
Context-sensitive design
Design for values
Circular economy

ABSTRACT

Water scarcity in arid regions has driven the spread of desalination. These systems contribute to water access but come at an intensive energy cost, and lead to brine discharge and associated environmental impacts. This work aims to investigate emerging societal issues and tensions when developing and implementing a thermal desalination system to produce irrigation water in the South of Spain. This has been done in a demonstration system for solar desalination able to recover water and salts from desalination brine. For this purpose, a context-sensitive design exercise has been implemented. First, tensions between social values expressed by diverse stakeholders have been identified. Then, a set of technical scenarios for the full-scale implementation of the system were designed and evaluated, comparing them to conventional membrane desalination. The analysis indicates high economic and energy costs to avoid the environmental impacts of increasing water production.

1. Introduction

Seawater desalination capacity has been constantly increasing worldwide since the 80's, and it is expected to double its capacity by 2030 [24]. The main challenges of seawater desalination are [71,73]: 1) to obtain added value recovering resources from brine (and avoiding brine release into the sea and potential impact on marine ecosystems), 2) to decrease the large amount of energy that these processes require, and 3) to decarbonize seawater desalination and reduce greenhouse gas emissions.

Regarding brine management, the zero liquid discharge (ZLD) concept has emerged as an environmentally friendly approach to seawater desalination [75]. ZLD refers to avoiding releasing brine into the environment by means of recycling all of it. In seawater desalination,

---

Abbreviations: CAPEX, Capital Expenditures; CIEMAT, Centre of Energy, Environment and Technology Research.; CSP, Concentrated Solar Power.; GDP, Gross Domestic Product; GHG, Greenhouse Gas; LCOE, Levelized Cost of Electricity.; LCOW, Levelized Cost of Water.; $LCOW_{NR}$, Levelized Cost of Water without considering the revenues from NaCl selling.; LCS, Levelized cost of NaCl.; MED, Multi-effect distillation.; NF, Nano-filtration.; OPEX, Operating expenditures; RO, Reverse Osmosis.; SAM, System Advisor Model; SEC, Specific Energy Consumption; Th Cryst, Thermal Crystallizer; ZLD, Zero Liquid Discharge..

* Corresponding author.

E-mail address: gonzalo.gamboa@uab.cat (G. Gamboa).

https://doi.org/10.1016/j.desal.2024.118213
Received 18 June 2024; Received in revised form 27 September 2024; Accepted 14 October 2024

ZLD can be met by increasing the recovery ratio (i.e., the share of distilled water out of processed water), which allows to recover salts and added value elements (such as Li, Co, Mg) whose availability is becoming increasingly limited [10,43,74,77]. However, achieving ZLD would also entail increasing energy consumption and economic costs.

In terms of energy consumption, there are several works in the literature dealing with efficiency improvements of desalination processes [12] by process optimization [2,32,44,68,76] and/or exploring and developing new technologies [31,44,69,72].

Decarbonization would be achieved by spreading the use of renewable energy sources. In fact, solar energy powers about half of the worldwide renewable desalination capacity, out of which 19 % is thermal solar energy [1]. Also, thermal desalination can achieve higher concentration factors than the most widely applied desalination process (i.e., reverse osmosis) [72]. Therefore, thermal desalination can play an important role in both decarbonizing seawater desalination and achieving ZLD. Moreover, recovering and valorising resources from brine (e.g., Sodium, Lithium, Magnesium and Calcium salts, and other minerals) would importantly contribute to the economic viability of thermal desalination technologies and to circular water economy.

However, social acceptance is one of the most limiting factors affecting the development of seawater desalination, together with costs of water production, environmental requirements, financial support, and legal certainty [64]. Several studies corroborate that the environmental impact on the marine environment and on sea-based activities (e.g., surfing, fishing, tourism) can have an important role in generating opposition to desalination projects, as well as lack of trust in institutions in charge of managing impacts, or the lack of public participation in the planning or in the environmental impact assessment processes [36,53,64,78,79]. Also, large land occupation may become an important constraint, above all in places where several socioeconomic activities compete for land (e.g., tourism, agriculture, energy production). For instance, Fornarelli et al. [14] have shown, for a case study in Australia, that disturbance of the beach and sea-based recreational activities, as well as impacts on residential development in the local area may act as factors influencing social acceptance.

On the other side, a perceived threat to water supply, either due to a mismatch between demand and supply and/or to the state of water sources, may have a very important role in fostering social acceptance of desalination technologies, as well as the inclusion of public participation in public decision-making [36]. In relation to this, these authors propose the following: a) to obtain reliable information on the status of water supply and demand and the status of water sources, b) to assess the environmental and socioeconomic impacts of desalination plants, c) to fully disclose the outcomes of this assessment to the public to meet transparency, and d) to value public opinions and incorporate cost-effective modifications to the desalination projects according to these opinions.

Several studies have incorporated public participation to evaluate and compare, from a diversity of perspectives, either water management options or desalination project alternatives.

These studies have applied multicriteria frameworks combined with different degrees of participation, from the more technocratic to the more participative. Aliewi et al. [4], Marini et al. [37] and Ibrahim et al. [21] take a more technocratic approaches based on expert knowledge (e.g., water managers and planners) to evaluate and compare water management options. Experts define alternatives, indicators and criterion weights.

Heck et al. [18] include a wider audience through surveys, but limits their participation to prioritize management objectives (i.e., define criterion weights) and to identify divergent opinions about desalination projects.

Domènech et al. [11] discuss the desirability and feasibility of non-conventional water sources, which are evaluated under a set of indicators derived from different social perspectives (i.e., public local and national authorities, water supply and technology companies, academics, neighbor associations, and environmental non-governmental organizations) and weights derived from the growth and degrowth narratives.

Paneque-Salgado et al. [51] carry out a participatory multi-criteria evaluation engaging a wide range of stakeholders (several decision makers, business organizations, citizen's organizations and experts) to define the problem, alternatives and evaluation criteria, and to analyse and discuss the results of the evaluation, with the ultimately goal of understanding the social and institutional context, identifying water management options and evaluating them from plural perspectives.

Even though these studies incorporate different types of stakeholders, public participation is limited to structuring the problem in terms of defining alternatives, evaluation criteria and criterion weights. The analysis and discussion of societal value tensions arising from the evaluation is left to researchers.

Palmeros-Parada et al. [49] take a step forward in this regard. They identify social values and concerns through interviews and workshops, incorporate some modifications to the original system according to societal values identified, evaluate environmental and socioeconomic impacts of desalination alternatives under stakeholders concerns, and openly discuss the tensions emerging from the evaluation with stakeholders (See also [34,35] for more details on the same case study).

The present work takes a step further in achieving the four recommendations made by Liu et al. [36] mentioned above. Distinctively, this work is based on a continuous feedback loop with stakeholders considering then one of the main objectives of the open innovation. In this work, the outputs obtained from the stakeholders (i.e., societal values and value tensions) were the basis to define the technical scenarios and the evaluation criteria. Additional to the inclusion of stakeholders in the problem structuring and evaluation, it promotes an informed discussion about societal tensions and provides some consideration to design policy recommendations aimed at implementing sustainable desalination technologies.

In fact, the aim of this work is not to design a thermal desalination plant with resource recovery, but to use the design of such a system to explore its societal implications with explicit recognition of emerging tensions between societal values around it.

To do so, this work puts forward a context-sensitive design approach that explicitly integrates societal values in the design of thermal desalination technologies. The approach is applied to a demonstration case study within the WATER MINING Horizon 2020 project. The demonstration took place in Almería, a water-stressed region in the South of Spain with important tourism and agricultural sectors. The project aims to bring circular economy to the water sector by recovering additional water and salts from desalination brine, all of it using thermal solar energy as the main energy source.

2. Materials and Methods

To engage stakeholders in participatory research for technological innovation process, a “context-sensitive design approach” [49] has been followed. The approach takes elements from Value Sensitive Design [89,90], a design methodology to explicitly integrate societal values in the design of technologies. The approach also incorporates elements of sustainable design [46,47] and participatory assessments [15]. It explicitly incorporates diverse, even contrasting, points of views regarding desalination technologies to consciously consider societal aspects into emerging technologies, which are often developed in processes that are blind to the context and the stakeholders' realities [80].

Following Palmeros-Parada et al. [49], our approach takes a responsible innovation perspective, which is aimed at making the innovation process more anticipatory, reflexive, and responsive by promoting a strong participation of stakeholders [38] in all stages of the research and innovation process.

For this, two phases have been implemented: Phase 1 (months 1–14), when technical and societal aspects of the thermal desalination systems were identified, such as societal values and concerns, and value tensions and uncertainties about thermal seawater desalination. In Phase 2 (months 15–35), technical scenarios were developed based on the findings from Phase 1, evaluated and brought to stakeholders to discuss value tensions and to identify questions for further research.

For this purpose, the following process took place (Fig. 1). First, researchers proposed a thermal desalination system that was presented and discussed with stakeholders. Then, in-depth interviews to key informants and workshops with stakeholders from different sectors were held to identify societal values around thermal seawater desalination. *Values* refer to aspects that were considered important for the thermal desalination technologies and were identified from value judgements and norms expressed by stakeholders.

In this step, *value tensions* were also identified. These tensions emerge as aspects of the technology or ways of implementing can contribute and oppose several values at the same time, and bring forth uncertainties. For instance, “this technology can greatly contribute to climate change mitigation, but its costs make it economically inviable.”

Based on the outcomes of the previous activities, a set of technical scenarios were developed by the researchers. These technical scenarios are different technical configurations of the originally proposed system, which deal with the value tensions identified previously.

Then, societal values were translated into evaluation criteria used to assess the socioeconomic and environmental impacts of the technical scenarios. The outcomes of the evaluation were finally presented and discussed with the stakeholders, from which some recommendations for policy makers are drawn.

The next subsections present the case study and the different methods applied during this participatory research process.

2.1. Case study

Almería, a Spanish province located in the south of Spain, is a well-known region due to its relevance regarding highly intensive vegetable production in greenhouses, with productivities doubling those of open-air production. In monetary terms, the export of fruits and vegetables from Almeria means half of the value of Andalucian exports, and about one fifth of the Spanish exports. Agriculture in Almería represents about 17 % of the Gross Domestic Product (GDP) of the province, while the share of GDP of the agriculture sector in Spain is about 3 % [23].

With a population of about 728 thousand inhabitants, the agricultural sector employs about one fourth of the working population, while in Spain the occupied population in the agricultural sector is about 4 %.

Regarding water use of agriculture, more than 32.000 ha of greenhouses for vegetable production consume about 160 Hm^3 of water each year, which means 5.000 m^3/ha [22]. According to data from INE [22] and MAPA [41], agricultural water consumption per hectare to produce vegetables is about the same at the level of Andalucía and Spain. However, the productivity of greenhouse vegetable production in Almería is twofold compared to the average vegetable yield of Andalucía and Spain [41]. On other side, water use in agriculture represents about 80 % of water usage in the Almería province and about 60 % is groundwater [26], which is severely overexploited and/or polluted according to the European Water Framework Directive assessment [81].

Under the framework of the European H2020 project WATER-MINING (Next generation water-smart management systems: large scale demonstrations for a circular economy and society – watermining.eu), the use of Nanofiltration (NF) as a pre-treatment in solar-powered Multiple Effect Distillation (MED) for the removal of divalent ions in seawater aiming to increase the recovery ratio of the desalination process has been evaluated. The public research centre Plataforma Solar de Almería-CIEMAT is responsible for this case study, which consists of demonstrating that, through solar thermal desalination, it is possible to improve the sustainability of current desalination technologies by achieving higher concentrations leading to ZLD processes, thus enabling the production and valorisation of high-quality salts and water suitable for use in the agricultural sector. It should be noticed that conventional technologies, such as RO, cannot achieve ZLD due to the limitations of the osmotic pressure [66].

2.2. Desk study and identification of relevant stakeholders

During months 1 to 10 (Sept 2020 – June 2021), a literature review was performed to identify societal values and value tensions around seawater desalination and the recovery of added-value products from the brines. The results of the review have been published in Palmeros Parada et al. [48].

During this time, an identification of stakeholders relevant to seawater desalination in the Almería region was performed. This task was performed following the different stages of the desalination process, differentiating stakeholders between the following categories:

- **Upstream stakeholders:** Supply chain stakeholders are those that supply the goods or services to be delivered (e.g., suppliers of goods or services, manufacturers, subcontractors, suppliers of technologies),

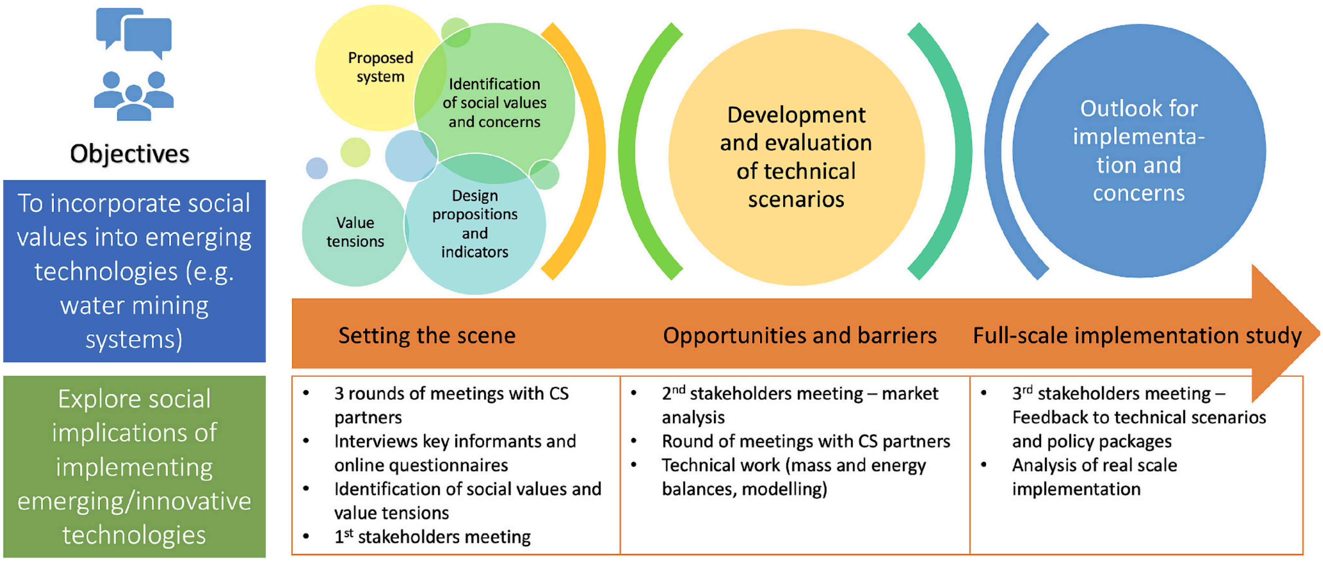

Fig. 1. Objectives, steps and activities of the Context-Sensitive Design approach (source: Own elaboration).

- **Downstream stakeholders:** The paying customer and those individuals or entities that will make use of the products or technologies (e.g. end-users of the products or by-products, intermediaries, clients, the marketplace, buyers and/or future operators of the technologies developed in the project),
- **Internal stakeholders:** Individuals or groups that are connected to the project and have strong influence in its success (e.g., project partners, top leadership and management, the executive board, managers and other staff, investors, project team), and
- **External stakeholders:** the general community and other individuals that will be impacted by the project, whose support is vital for its success (e.g., affected communities, concerned groups, knowledge networks, government, regulators, non-governmental organizations, activist groups, interest groups, media).

The final list of stakeholders included more than 40 people from the local and regional public administrations, the desalination and water industry, the agricultural sector, irrigation communities, non-governmental organizations, and the academy and education sector.

2.3. *Interaction with project partners and stakeholders*

A series of in-depth interviews with key informants, an online survey, meetings with technical project partners and workshops with stakeholders were carried out.

Between months 1–14 a series of meetings were held between the researchers and technical project partners. The last were responsible for the design, development and testing of the technologies. These meetings were aimed at:

1. familiarizing the researchers with the thermal seawater desalination technologies and the technical partners with the context-sensitive design approach,
2. identifying technical aspects of thermal seawater desalination (main products, technologies and design variables), and
3. identifying expectations, research focus and concerns about the technical systems of technical researchers (i.e., project values).

Between months 6–10 interviews and online surveys were carried out to identify stakeholder values specific to this case study. The interview guide and the online survey included questions about the advantages and disadvantages of thermal desalination technologies, the potential use of recovered resources from seawater and desalinated seawater for irrigation, and the quality requirements to use recovered resources and desalinated seawater.

The survey was shared with 20 stakeholders, from whom 8 responses were obtained. Five key informants from the agricultural sector (2), a financial company, an environmental non-governmental organization and a public authority were interviewed. Key informants are well-informed, reflective people, who have first-hand knowledge about an issue and are willing to talk extensively with the researchers [3,54,58].

The interaction with the whole group of stakeholders took place in three workshops, where stakeholders from different backgrounds and points of view came together to share ideas or express concerns about the technologies developed in the project and learn from the experiences of one another. Workshops were structured beginning with presentations for the whole group, followed by small group discussions and a plenary to share the outcomes of discussions.

The first workshop was held in October 2021 (month 14) and was aimed at presenting the project, its objectives and the case study. Additionally, the workshop aimed to validate the societal values identified by means of the literature review, in-depth interviews and meetings with technical researchers.

A second workshop was held in February 2022 (month 18) and was aimed at analysing market barriers and enablers. Even though this workshop was not directly related to the context sensitive design process, it produced complementary information to develop the technical scenarios.

The third meeting took place in February 2023 (month 30) and was aimed at presenting, analysing and discussing the technical scenarios (see 0 Technical scenarios) and their performance, and to identify and validate emerging societal tensions.

2.4. *Identification of societal values and value tensions*

Project documents and transcribed in-depth interviews and surveys were analysed following the inductive interpretative process of open coding to identify project and social values, respectively. Open coding refers to the process of breaking down data in different meaning units, identifying data units (e.g., sentences of different length) representing an example of a general phenomenon [8]. In this case, the categories identified from this process (i.e., the codes) were the societal values, which were identified from expressed value judgements during the interviews and surveys (expressed in objectives, concerns, and expected benefits or drawbacks related to the technology and its implementation). For instance, the statement "*thermal seawater desalination systems should decrease the pressure on the environment by reducing the generation of brine*" contains the value environmental protection, while the sentence "*a drawback is that the high investment costs of thermal systems may hinder the economic viability of these projects or imply high water prices for the final consumers*" indicates that economic viability and distributive justice are relevant values for implementing these technologies. Technical scenarios.

2.4.1. *Water Mining System*

Based on the co-resource recovery business model archetype developed by Pereira et al. [55] and the Water Mining demonstration system, a large thermal desalination plant coupled with a hybrid gas-CSP plant was proposed as a base scenario (Scenario 1). The business model is based on a stable cooperative relationship (industrial symbiosis) among two partners sharing knowledge on the technical characteristics of the waste heat for its recovery and exploitation as a useful input for thermal seawater desalination, or a single partner operating both systems. Also, the business model is aimed at recovering and valorising resources from brine – in this case, NaCl – to contribute to circular water economy and increase the economic viability of thermal water desalination.

The entire system (Fig. 2) would be located inland to take advantage of greater solar irradiance than on the coast and avoid corrosive environments that reduce the efficiency of the mirrors of the solar thermal collectors. The thermal desalination system proposed by the WATER-MINING project would use the waste heat from the Rankine power cycle.

The hybrid gas-CSP plant is composed of parabolic troughs, thermal storage tanks and a Rankine power cycle as well as an auxiliary natural gas burner to allow continuous operation of the systems 24 h. It has been considered an availability of the plant of 96 %. The CSP plant has been sized to provide the required thermal energy from the turbine exhaust steam to the MED unit and the thermal crystallizer. In addition, apart from producing electricity for the grid, the CSP plant provides the electricity required by the electricity consumers (i.e., pumping station, NF, MED, vacuum pump and mixer).

It has been considered that the seawater is transported 50 Km inland from the seaside and 300 m above sea level, at an average velocity of 1 m/s by a pipe of 24-in. nominal diameter.

Then, seawater passes by a nanofiltration (NF) unit, which retains divalent ions (Ca^{+2}, Mg^{+2}, SO_4^{2-}) by 95–99 %, and Sodium (Na) and Chloride (Cl) by 12–14 %.

The outflow of the NF goes to the Multi-Effect Distillation (MED) unit, which can operate at 90 °C and a recovery rate of 86 % thanks to the absence of divalent ions. If NF were not applied, the MED would have to operate at 70 °C and a recovery rate of 36 % to avoid scaling due to the presence of divalent ions. On one side, the use of a NF before the MED implies an important improvement in the recovery rate (and in the

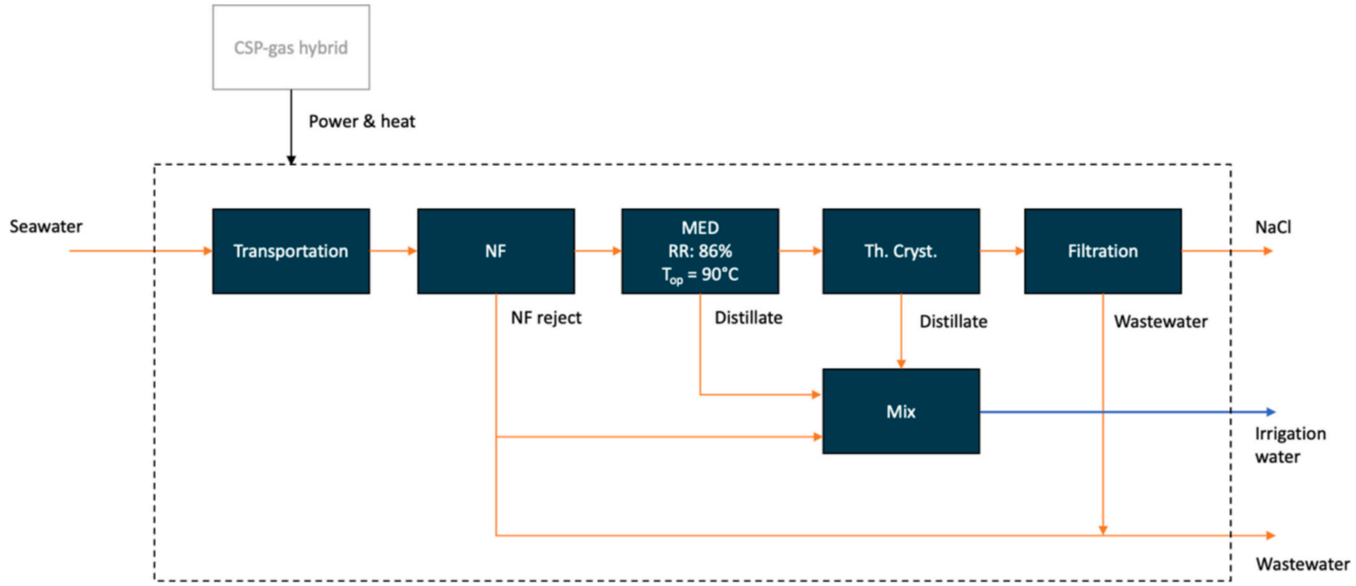

Fig. 2. Thermal desalination system proposed by the WATER-MINING project.

concentration factor). On the other side, a small fraction of the NF concentrate could be mixed with the final distillate to provide divalent ions necessary for irrigation purposes.

The concentrate from the MED goes to a thermal crystallizer coupled with a filtration system (belt filter) that evaporates the inlet solution, reaching the saturation point and obtaining NaCl crystals with a moisture content of 5 %.

Finally, the MED and Thermal Crystallizer distillates are mixed (and mineralized) with part of the NF reject to produce irrigation water with a salinity below 2.000 g/m^3 and the following salts content limits, which are considered normal values for irrigation: 20 meq/l of Ca^{2+}, 5 meq/l of Mg^{2+}, 40 meq/l of Na^+, 30 meq/l of Cl^- and 20 meq/l of SO_4^{2-} [60]. The rest of the NF reject is mixed with the brine produced in the vacuum filtration.

2.4.2. *Development of Technical Scenarios*

Different technical scenarios were developed to explore different technical configurations of thermal desalination to respond to the identified value tensions. The scenarios are tools to explore different technology development pathways, allowing to anticipate potential impacts, and to explore and discuss the identified tensions more concretely [49]. An iterative process between a desk study to develop, model and simulate the scenarios, and meetings with technical partners and other project partners to validate the scenario progress was held. The desk study started analysing which tensions could be explored through technical scenarios and their evaluation. Once this focus was identified, the scenarios were developed considering four main variables: 1) process and technology, 2) product and by-products, 3) scale and supply chain and 4) raw materials and utilities, in perspective of the identified societal aspects [46].

A conventional RO desalination system is considered as a benchmark for comparison. This scenario considers RO desalination located seaside, powered with electricity from the grid and without brine treatment. Seawater would be transported 5 km inland, and 50 m above the sea level. A Specific Energy Consumption (SEC) of the RO system of 2.5 kWh/m^3 and a recovery ratio of 50 % have been considered in this study [2].

Notice that the technical scenarios proposed do not consider the pre-treatment processes before the RO and NF systems. In terms of comparison with the benchmark scenario, both the RO and the NF + MED processes would need similar pre-treatment of seawater, such as micro or ultrafiltration systems [62,65].

2.5. *Attributes and indicators*

Following Gamboa et al. [15,82], societal values and concerns were translated into a set of multi-dimensional attributes and indicators representing different views present in society. Attributes refer to the elements used within the specific narrative to describe a system: a description of an observable relevant quality. For example, the assertion that “brine generation is one of the big challenges of seawater desalination” contains a value judgment, which is used to identify “brine generation” as an attribute within it.

To perform a quantitative characterisation of the system under study, it is necessary to define the formal categories to measure and monitor the state of the system according to each criterion. Indicators can be defined as the image of an attribute, formalised in terms of a specific measurement [83]. For example, the “amount of brine generated measured in tonnes per day” when desalinating seawater can be used as the indicator for the criterion “brine generation”. The value of the indicator (i.e., the state of the variable) provides information about the condition and/or the trend of the criterion describing the system.

The technical scenarios were evaluated under this set of multi-dimensional indicators (Table 1), which enable the researchers and stakeholders to discuss the emergent societal tensions around the full-scale implementation of thermal desalination technologies.

As the main objective of this work is not to discuss the technicalities of the calculations and modelling exercises, the description of the calculation methods and the main assumptions are presented in the Supplementary materials. Here, some general description of the methods used and assumptions made to calculate the indicator scores are provided.

Mass and energy balances of the scenarios were used to calculate the value of most of the indicators. (e.g., amount of irrigation water, brine generation, energy consumption, NaCl recovery). The assumptions made to develop the mass and energy balances are presented in the description of each scenario (see section 3.2 Technical scenarios).

CO_2 emissions were calculated considering an emission factor of 0.37 TCO_2/MWh of electricity generated in a combined cycle power plant [57] for scenarios considering a hybrid gas-CSP plant and an emission factor of 0.259 TCO_2/MWh of the Spanish electricity mix for the benchmark RO scenario.

The economic performance of the scenarios was evaluated by the levelized cost of water (LCOW) and the levelized cost of NaCl (LCS), calculated following Papapetrou et al. [52] (See Eq. 1 and Eq. 2 of

Table 1
Attributes and indicators to evaluate and compare technical scenarios.

Attribute	Indicator	Unit	Objective/s
Irrigation water	Volume of irrigation water	[m^3/d]	- Maximize production of irrigation water - Support agricultural sector
Energy consumption	Electricity consumption	[GWh/y]	- Minimize energy consumption
Brine generation	Amount of brine	[T/d]	- Zero liquid discharge - Minimize generation of residues
Salt production	Volume of NaCl production	[T/d]	- Recover resources - Valorise ZLD
GHG emissions	CO_2 emissions	[TCO_2/y]	- Decarbonize the desalination sector
Land use of the thermal collectors' field	Surface of land use	[ha]	- Minimize land use - Minimize land competition of economic activities
Cost of water production	Levelized cost of water - LCOW	[€/m^3 irrigation water]	- Economic viability of desalination - Reduce water prices - Support agricultural sector
Revenues	Revenues from NaCl and irrigation water	[€/y]	- Economic viability of desalination

Supplementary material).

The fixed-capital investment (CAPEX) and operating expenditures (OPEX) were calculated following Akhter et al. [3]. The percentages of different costs components were adjusted to the Spanish reality according to [84] and expert consultation[1]. The LCOW of scenarios 1 to 4 incorporates the Levelized Cost of Electricity (LCOE) of the gas-CSP hybrid plant, which is used to calculate the energy cost of producing desalinate water. More details about the parameters of the CSP plant can be found in the Supplementary materials.

The costs of brine disposal have not been considered here because of its low irrelevance compared to energy or other operational costs [28].

The design and simulation of the CSP plant has been performed by SAM software (https://sam.nrel.gov/). The software also provides information on land use and the cost of the equipment, which have been taken to do the cost analysis, also considering information from CSP experts.[1] The software also calculates the LCOE, which was used to calculate the operational costs of the desalination plants using thermal technologies. To calculate the LCOE, the average price of natural gas in the wholesale Spanish market during the five-year period 2018–2022 has been considered (39.3 €/MWh). For the benchmark RO scenario, the average price of electricity for industrial users in Spain during the same period was assumed (83.7 €/MWh).

In this work, the economic costs of energy are only derived from the consumption of electricity. Thermal energy is assumed to have zero economic cost as it comes from waste heat from the turbines of the hybrid gas-CSP, which is an available by-product of electricity generation (industrial symbiosis).

Finally, revenues were calculated according to the amount of irrigation water, NaCl and mixed salts produced, considering prices of 0.45 €/m^3, 110 €/T and 10 €/T (U.S. [16]), respectively. Prices of pure NaCl considered in this work are coherent with values between 80 and 150 $/Ton reported in Micari et al. [40].

3. Results

In this section, the outcomes of the "*context-sensitive design approach*" for the Almeria case study are presented. First, a summary of the societal values and value tensions are described. Then, technical scenarios developed to consider value tensions and uncertainties are presented. Finally, the performance of the different scenarios is presented and compared according to the indicators defined based on social values and concerns.

3.1. Societal value tensions

The first outcome of this research is the identification of societal values. Here, the main value tensions arising these values are reported, which have been considered to develop a set of technical scenarios. The ideas expressed in these paragraphs are not facts. They are based on the perceptions and expectations of stakeholders and project partners, which will be investigated in the assessment and analysis of technical scenarios.

- Energy consumption, climate change and land use. Conventional desalination systems have high energy consumption and, consequently, greenhouse gas emissions derived from a fossil-based electricity system. Thermal desalination based on solar energy or waste heat is seen as a way to decarbonize seawater desalination. However, extensive land use of renewable energies may hinder the development of thermal systems, above all in places close to the coast where other economic activities, such as tourism and agriculture, compete for land.
- ZLD, market uncertainties and economic viability. Thermal seawater desalination would be a way to reach ZLD (due to the possibility to achieve much higher concentration factor in MED by removing divalent ions by NFs) and importantly reduce impacts on marine ecosystems due to brine releases. However, thermal technologies are more expensive than conventional ones and make their economic viability more uncertain. The valorisation of resources recovered from brine (e.g., NaCl) may increase revenues and economic viability of thermal desalination.
- Affordability, distributive justice and societal acceptance. ZLD can increase the costs of desalination, raising the question of who could and should pay for it. The issue is relevant especially if water is produced for irrigation purposes in a water-stressed semi-arid region with an export oriented agricultural system. It raises the question of whether desalinating seawater for irrigation in this context is environmentally friendly at all, even if based on renewable resources.

3.2. Technical scenarios

The development of the technical scenarios and their evaluation under a set of multi-dimensional indicators was the result of the second phase of this work. For this, energy source, location (inland, seaside), and degree of resource recovery (NaCl, water only) were identified as main variables. All scenarios were aimed at processing 30,000 m^3/d of seawater.

Scenarios 0 and 1 are already explained in section 0 Technical Scenarios. Scenario 0 considers an RO system located on the coast, with a SEC of 2.5 kWh/m^3 and a recovery rate of 50 %. Scenario 1 is the system proposed by the Water Mining project (See section 2.4.1 Water Mining System).

3.2.1. Scenario 2. Thermal desalination inland

Scenario 2 (see Fig. 3) has been designed without considering the thermal crystallizer. Therefore, it generates brine and does not valorise resources from it (i.e., NaCl), but it requires lower thermal energy consumption, land use and economic costs.

Seawater is transported to a thermal desalination plant located 50

---

[1] Personal communication E. Zarza.

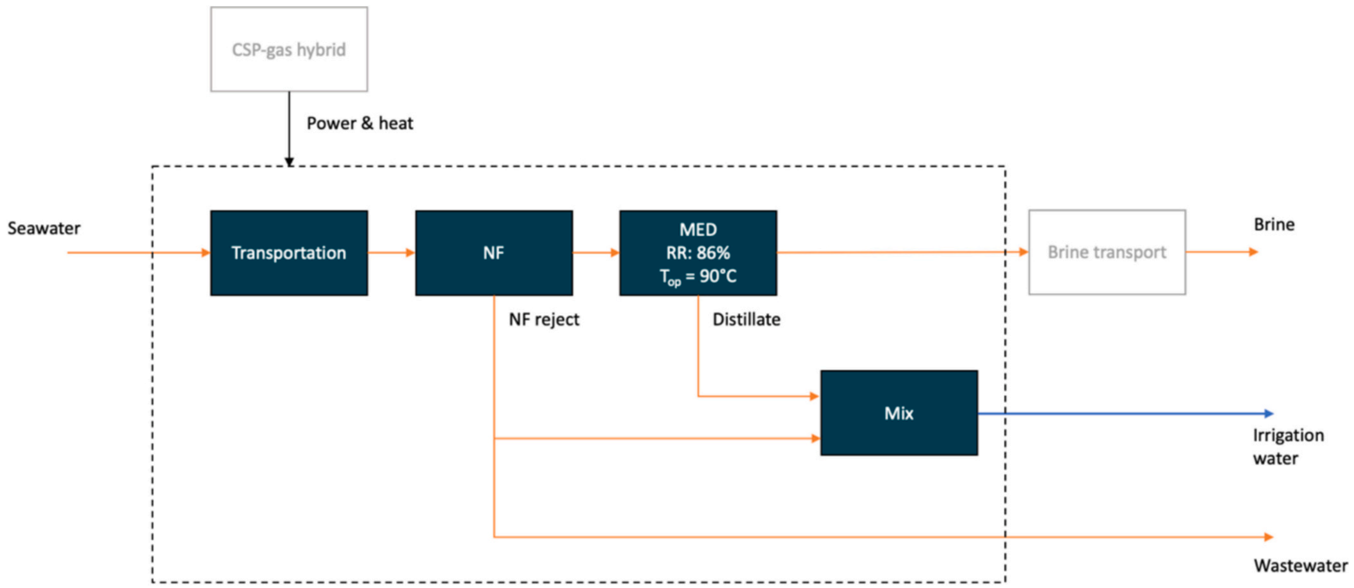

Fig. 3. Scenario 2. Thermal desalination inland.

Km inland and 300 m above the sea level, coupled with a hybrid gas-CSP plant. The scenario considers a nanofiltration process to extract divalent ions from seawater, so the MED can operate at 90 °C and reach a recovery ratio of 86 %. A mixer adds part of the NF rejection to the MED distillate to produce irrigation water, and the brine from the MED and the NF rejection is managed afterwards.

3.2.2. *Scenario 3. Thermal desalination inland ZLD and NaCl recovery*

In Scenario 3 (see Fig. 4), a second block chain composed of a MED, a Thermal Crystallizer plus Filtration and a Mixer has been added to achieve ZLD, using then large part of the NF rejection as feed for the second MED system. This MED operates at 38 % recovery rate and at 70 °C due to the presence of divalent ions that can produce scaling in the MED if operating at higher temperatures. As the NF rejection contains salts other than NaCl, the rejection of the filtration process is water with a high content of mixed salts, including NaCl.

3.2.3. *Scenario 4. Reverse Osmosis + Thermal desalination (ZLD) Inland*

This scenario (see Fig. 5) has been designed to achieve ZLD with an RO system coupled with a thermal system (MED and Thermal crystallizer).

As in scenarios 1, 2 and 3, the whole hybrid gas-CSP plus desalination system is located 50 Km inland and 300 m above the sea level. It allows to treat the RO reject with the MED (which has to be located next to the CSP plant to be driven by the exhaust steam turbine) in order to achieve ZLD.

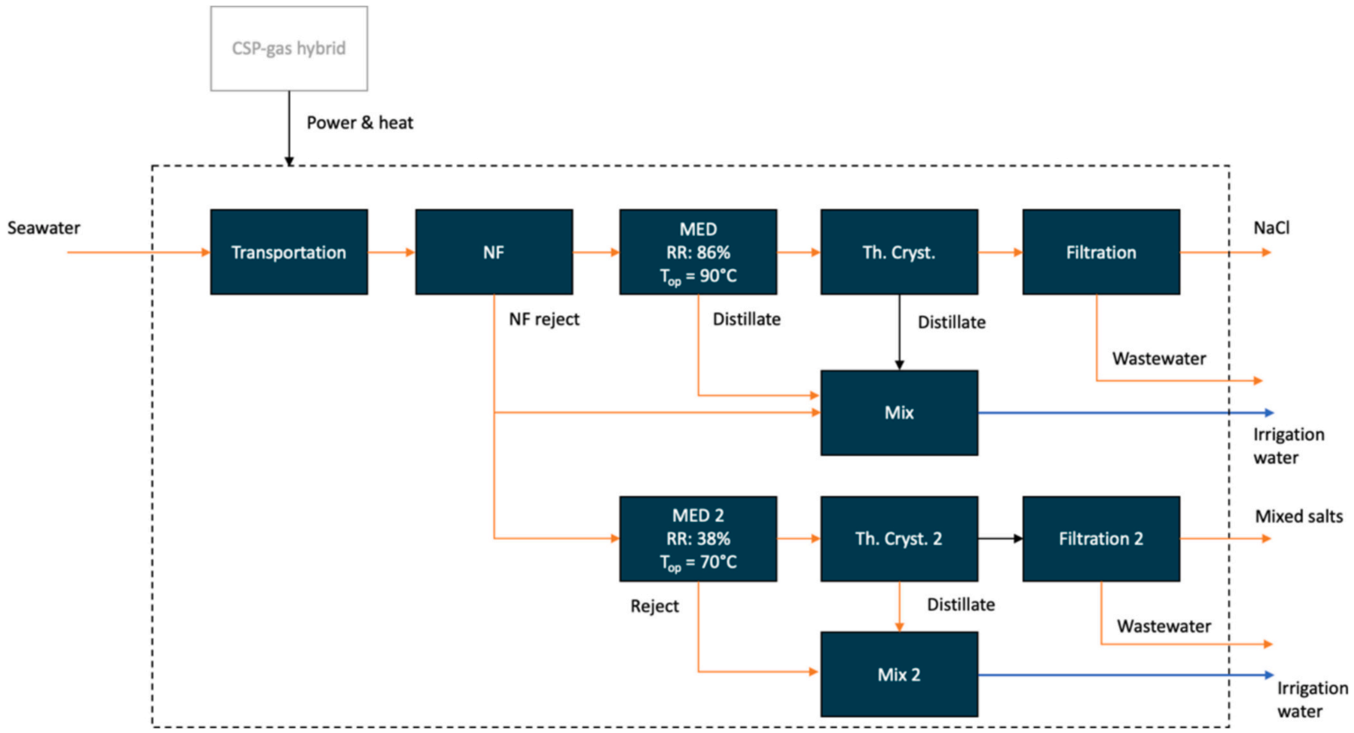

Fig. 4. Scenario 3. Thermal desalination inland, ZLD and NaCl recovery.

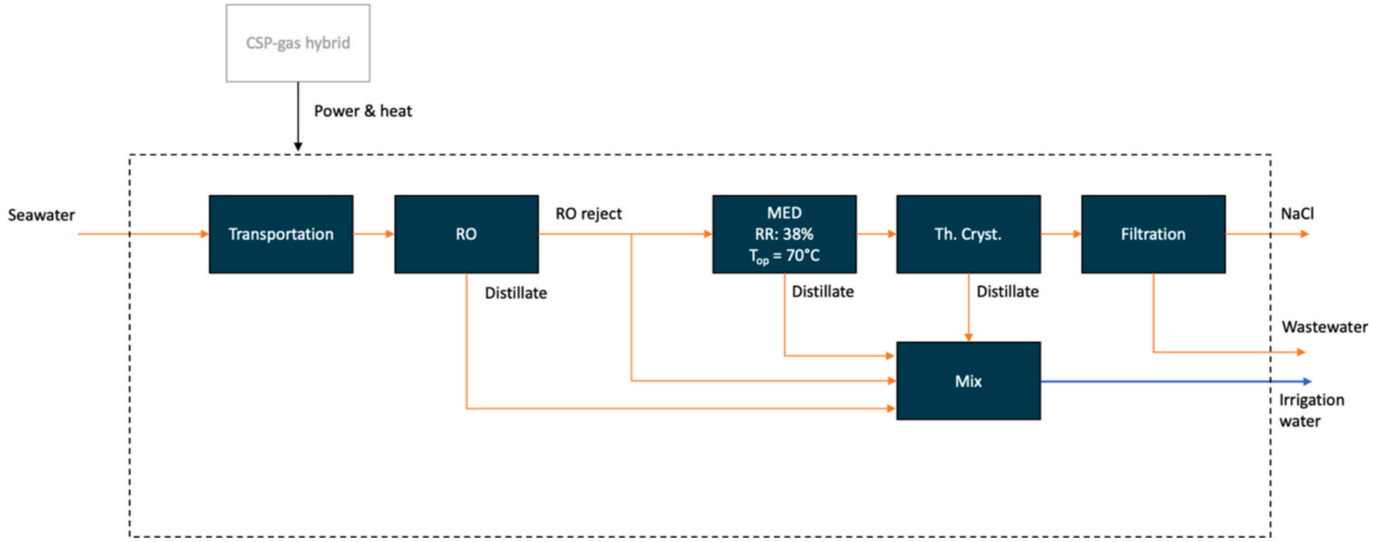

Fig. 5. Scenario 4. Reverse osmosis + Thermal desalination Inland, ZLD.

The RO is powered by the CSP plant. It works at a SEC of 2.5 kWh/m^3 and a recovery ratio of 50 % [2]. As the RO reject contains divalent ions, the MED operates at 70 °C and a recovery rate of 38 %. Higher temperatures and recovery ratios cannot be achieved due to scaling. Also, including a NF before the MED to extract divalent ions would produce high salinity slurry in the MED, which would surpass the processing capacity of the thermal crystallizer. Therefore, NF is not included in this scenario.

Then, part of the RO rejection is mixed with the MED and Thermal crystallizer distillates to produce irrigation water with a salinity and salts content limits similar to those indicated in Scenario 1.

3.3. *Discussion of scenarios performance*

The performance of all scenarios is presented in Table 2, which allows the reader to recognize a strong tension between increasing water recovery and avoiding brine discharge versus the costs associated with it.

In the following subsections, these tensions are reviewed following the value tensions mentioned in section 3.1.

3.3.1. *Energy consumption, CO_2 emissions and land use*

As it can be seen in Table 2, Scenario 0, presents the lowest energy consumption and CO_2 emissions to process 30,000 m^3/d of seawater. However, as the recovery rate is only about 50 %, it produces less irrigation water compared to other alternatives. In other words, when processing almost a double amount of water to provide the same amount of irrigation water as the other options, RO would double the total energy consumption, brine release and CO_2 emissions. In fact, when electricity and CO_2 emissions are calculated per cubic meter of irrigation water produced, Scenario 0 performs in between the rest of scenarios.

When scenarios 1 (Water Mining scenario) and 2 (which disregards the thermal crystallizer in its configuration) are compared with Scenario 0, they show an increase in the production of irrigation water, together with a significant reduction in brine generation (i.e., reject from the NF and from the MED). However, those improvements entail an important land requirement.

In case that Scenarios 3 and 4 are compared with Scenario 0, the first ones result in much larger amount of irrigation water (about 90 %) with respect Scenario 0, being the energy consumption per cubic meter of irrigation water 106.5 and 90.5 % of the benchmark scenario,

Table 2
Performance of different scenarios, when processing 30.000 m^3/d of seawater.

Indicators	Units	Sc0	Sc1	Sc2	Sc3	Sc4
		RO / Seaside	Thermal / Inland / NaCl Recovery	Thermal / Inland	Thermal / Inland / ZLD	RO + Thermal / Inland / ZLD
Volume of irrigation water	[m^3/d]	15,400	23,200	20,200	28,700	29,000
Land use	[ha]	–	282	154	462	392
Electricity consumption	[GWh/y]	17.1	32.8	32.6	33.9	29.2
	[kWh/m^3 irrigation water]	3.04	3.87	4.42	3.24	2.75
CO_2 emissions	[TCO_2/y]	4420	6795	6754	7029	6041
	[TCO_2/m^3 irrigation water]	0.79	0.80	0.92	0.67	0.57
Brine generation	[T/d]	15,450	6367	10,784	354	316
NaCl production	[T/d]	–	1285	–	1285	–
Mixed salts production	[T/d]	–	–	–	500	1540
$LCOW_{NR}^{1}$	[€/m^3 irrigation water]	0.87	1.74	1.73	1.47	1.16
Revenues irrigation water	[M€/y]	2.43	3.66	3.19	4.53	4.57
LCS	[€/T_{NaCl}]	–	23.4	–	19.0	13.4^{2}

Notes:
1) LCOWNR is the Levelized cost of water considering No Revenues from NaCl.
2) Levelized cost of mixed salts.

respectively. CO_2 emissions per cubic meter of irrigation water are 84.8 and 72.2 % of scenario 0, respectively. However, Scenarios 3 and 4 require larger land requirements due to the CSP plant.

In this sense, solar thermal desalination brings a tension around land use that, in the case of Almeria, needs a closer look. Locating the desalination plant on the coast provides direct access to seawater. But the extensive land use for solar field, as well as the losses in efficiency of mirrors and the lower solar irradiation on the coast, make it difficult to locate them in the coastline. Moreover, competition for land with other socioeconomic activities (e.g., agriculture, tourism and housing) may occur. Alternatively, transporting seawater inland, up the steep mountains around Almería, may seem inadequate considering the high energy requirements and economic costs of transporting seawater inland.

3.3.2. ZLD, market uncertainties and economic viability

ZLD is only possible with thermal technologies that allow achieving much higher recovery ratios/concentration factors [72,75]. In the case of the technical scenarios, the best results in these terms were obtained for Scenarios 3 and 4 that result in the lower brine rejection. It would allow to importantly reduce impacts on marine ecosystems due to brine releases. However, investment and operational costs of scenarios based on thermal technologies are higher than conventional ones (See Table SM3 in supplementary material) and make their economic viability more uncertain.

According to this, some stakeholders proposed to continue desalinating seawater with conventional RO systems with typical recovery rates of 50 % and releasing brine to the sea. They argued that this practice is not so harmful to the marine environment if done adequately. While this point has also been argued elsewhere [7,63], other studies show that brine discharge to marine environment may have adverse effect on water and sediment quality and on coastal ecosystems. These impacts depend on brine composition and temperature, which are determined by the water source, the desalination technology and chemical used in operation and maintenance of the desalination plant [50,85].

Most of the chemical additives used in desalination plants operation and contained in brine may have negative effects on the marine ecosystems if they are not well diluted and/or neutralized before being discharged into the sea [85]. However, it is hypersalinity of the brine that is of most concern. It can elevate water salinity at few kilometres from the discharge point [13] or exceed salinity environmental quality standards at the see bottom [56], impacting marine ecosystems [42,50,86] and biodiversity [59]. The extent of the impact of brine release would depend on the biological conditions of the receiving environment, the tolerance to salinity changes of affected marine communities and their ability to adapt or to move out of the affected areas [42,50,86,87], on the oceanographic conditions and its ability to provide sufficient transport capacity to dilute, disperse or degrade brine and residual chemicals [50,85]. In any case, limitations have been found when monitoring brine dispersion [71] and its impacts remain difficult to predict [13,33,70].

On the other hand, the valorisation of NaCl from brine is important to make these technologies economically viable. Only scenarios recovering and valorising NaCl from brine generate enough revenues to afford the LCOW. However, it became evident that the amounts of recovered salts are so large that it is needed to question their market feasibility. The scenarios producing NaCl would arrive to produce about 40–60 % of the current Spanish sea salt production, in an already saturated domestic market [67].

To analyse this issue, the minimum amount of salts to be sold to reach the break-even point of irrigation water has been calculated, considering revenues from NaCl. That is, if no salts are valorised and sold in the market, all scenarios present a LCOW that significantly surpasses the price of irrigation water in Almería (0,45 €/m^3). Table 3 presents the LCOW of each scenario and the amount of NaCl and mixed salts that should be sold to reach a LCOW of 0.45 €/m^3; the price of irrigation water. As can be seen in Table 3, only scenarios 1 and 3 would reach the break-even point of irrigation water by selling 21.2 and 20.8 % of the NaCl produced, respectively, in each scenario. In the case of scenario 4, even if all mixed salts are sold, it would not reach the break-even point of irrigation water due to the lower cost of non-pure salts.

Table 3
Amount of NaCl and mixed salts to be sold to reach break-even point in irrigation water.

Indicators	Units	SC0	SC1	SC2	SC3	SC4
Amount of NaCl produce	[T/d]	–	1285	–	1285	–
Amount of NaCl to be sold	[T/d]		273 (21.2 %)		267 (20.8 %)	
Amount of mixed salts produced	[T/d]	–	–	–	500	1540
Amount of mixed salts to be sold	[T/d]					1540
Revenues NaCl and mixed salts	[M€/y]	–	8.33	–	10.29	5.40
LCOW[1]	[€/m^3 irrigation water]	0.87	0.45	1.73	0.45	0.63

Notes:

1) Levelized cost of water considering the minimum revenues from NaCl that makes the LCOW equal to the price of irrigation water (i.e., 0.45 €/m^3).

In this sense, the risk of turning brine discharge into solid residues may be avoided by substituting mined salts by sea salts. In this way, energy consumption, GHG emissions, ground water pollution, and several other environmental problems related to salt mining can be avoided. In Spain, one fourth of salt production is sea salt, giving it a wide range to substitute mining salts [67]. However, this may bring some socio-environmental impacts and benefits switch between territories that should be studied. For instance, this may entail more social nuisance in towns next to seawater desalination plant due to increased truck transit transporting the recovered resources and, on the other side, less economic benefits and less environmental impacts in mining areas.

It should be also noticed that, as a NF process has been applied, this NaCl could be considered micro-plastics free, which would give it an advantage in comparison with other types of sea salt.

Fig. 6 shows the results of the calculation of the $LCOW_{NR}$ (without the consideration of the revenues from NaCl) (Columns in the graph), the potential revenues from selling NaCl (red dots in Graphic) and the difference between $LCOW_{NR}$ and revenues (i.e., actual LCOW). The benchmark RO scenario presents a LCOW between 60 and 72 % of the rest of scenarios. Even though the inland scenarios have a relatively high cost of transporting water (about one fifth of the LCOW), the RO scenario still presents a lower LCOW when considering only the costs of desalination. In any case, the LCOW of all scenarios is above the price of irrigation water if the revenues of valorising and selling NaCl are not considered. Only the scenarios recovering and valorising resources from brine would become economically viable, especially those recovering NaCl (Scenarios 1 and 3).

Scenarios 3 and 4 present a good combination of technologies to achieve ZLD and valorise resource recovery. Even though they present the highest $LCOW_{NR}$ and largest land use within the compared alternatives, these scenarios perform better in terms of irrigation water production, minimizing brine generation, electricity consumption and CO_2 emissions per cubic meter of irrigation water and, in case of scenario 1 and 3, generating enough revenues to contribute to the economic viability of the proposed system.

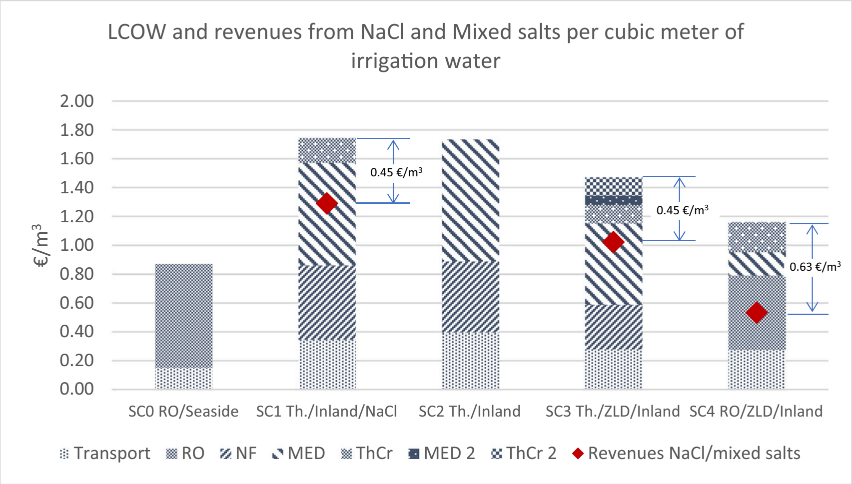

Fig. 6. Structure of levelized cost of water in different scenarios.

3.3.3. *Affordability, distributive justice and societal acceptance*

Implementing ZLD can increase the costs of desalination, raising the question of who could and should pay for it. The issue is relevant, especially if water is produced for irrigation purposes in a water-stressed semi-arid region with an export-oriented agricultural system. It raises the question of whether desalinating seawater for irrigation in this context is environmentally friendly at all, even if based on renewable resources.

Stakeholders participating in CoP meetings also argued that higher water costs derived from desalination, aimed at irrigation purposes, should be paid by end-users who make a profit out of it. This would entail studying the impact on the economic viability of vegetable production and on the local labour market that must be assessed and discussed.

These observations led to a reflection over the contribution of this system for a desirable circular economy, where there would be high costs to avoid the environmental impacts of providing scarce resources, such as water in a semi-arid water-stressed region, to highly resource-demanding and growth-oriented industries like greenhouse vegetable production.

In Almería, 12 out of 27 aquifers are overexploited, meaning that the annual withdrawals are higher than 80 % of the natural groundwater recharge [26]. According to Cabello et al. (2019), groundwater resources are over-drafted in Almería because the combination of intensive horticulture in greenhouses withdrawing very large quantities of water in some overexploited aquifers, and hyper-intensive olives and mix of open field fruits and vegetables drawing from aquifers with extremely low availability. It is also shown that the irrigation areas populated by greenhouse farming systems, extracting large amounts of groundwater, have introduced more alternative water sources such as surface, reclaimed and desalinated water. However, this strategy implemented in the past decade to replace groundwater for irrigation purposes has not delivered the expected outcomes, due to the combination of high energy cost of these technologies, and the increasing price of energy and decreasing price of crops [88].

Moreover, past experiences show that efficiency increases lead to an increase in resource consumption in the mid- and long-term due to the expansion of human activity thanks to the newly available resources [17]. In this case, increasing the amount of crop production per volume of irrigation water, would allow an expansion of the agricultural sector, or even the expansion of other sectors such as tourism, thanks to the availability of new resources if groundwater withdrawal is not forbidden and controlled.

Then, the question arises: Would it be sustainable to supply desalinated water to an export-oriented agricultural sector even if it was powered with solar thermal energy, considering the context of a water-stressed region where aquifers are already highly degraded? And without implementing strict policies or measures to avoid aquifers' overexploitation?

There is no easy answer in a complex context where an important part of the population directly or indirectly depends on (mostly) small farms of 2–3 ha, organized in cooperatives and closely related to the local identity.

It is concluded that the exercise of a specific technological intervention – resource recovery from brines – opened a conversation about what a circular economy looks or should look like in the region. Participating stakeholders concluded that water efficient agricultural production in Almería would nevertheless be desirable, and some of them proposed some conditions for it. In economic terms, some propose to apply a polluter pays principle when pricing desalinated seawater, offering conditioned subsidies or fiscal incentives to sustainable desalination systems, or implementing tiered pricing for the volume of water being used together with differentiated prices depending on the final use. Some recommended to raise public awareness by means of enforcing transparency around water and carbon footprints of agricultural products. Finally, some propose to limit and increase control over water extractions from degraded aquifers to prevent over-consumption of fresh water, or to avoid desalinated irrigation water being a complement to fresh groundwater, but a substitute.

4. Conclusions

This work is focused on the evaluation of the potential, from a social and technical point of view, of solar thermal desalination to recover water and salts from brine as well as to produce irrigation water in Almería. An exhaustive work has been done with technology developers and stakeholders in a context-sensitive design exercise. First, project and social values and value tensions were identified. Four technical scenarios were established and designed for the full-scale implementation of the system, to explore different technical configurations to respond to the identified value tensions. Scenarios were evaluated and compared with a conventional desalination RO system under a multi-dimensional set of indicators, including irrigation water production, energy consumption, land use, CO_2 emissions and economic performance.

From this evaluation, it has been demonstrated that the combination of thermal desalination and resource recovery technologies may significantly contribute to minimize residual brine and CO_2 emissions, and to maximize irrigation water production compared to conventional RO system. However, large land use, competition with other socio-economic activities and efficiency considerations of thermal technologies imply an important constrain to locate them near the coast. Transporting seawater inland represent between one fifth and one fourth of the cost of water.

Thermal technologies can play an important role to achieve ZLD, avoiding the environmental impacts of brine disposal. In this regard, only the scenarios that valorise the resource recovered from brine (i.e. NaCl) would reach the break-even point of irrigation water. However, the question remains whether it is possible to put all recovered resources on the market and avoid brine discharge becoming solid residues.

This work has raised important issues when discussing about what a circular economy looks or should look like in a water stressed region specialized in agricultural production for exports.

CRediT authorship contribution statement

Gonzalo Gamboa: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Patricia Palenzuela:** Formal analysis, Validation, Investigation, Writing – review & editing. **Rodoula Ktori:** Formal analysis, Writing – review & editing. **Diego C. Alarcón-Padilla:** Validation, Investigation. **Guillermo Zaragoza:** Project administration, Validation, Investigation, Writing – review & editing. **Samar Fayad:** Investigation. **Dimitros Xevgenos:** Funding acquisition, Project administration, Writing – review & editing. **Mar Palmeros Parada:** Conceptualization, Methodology, Supervision, Investigation, Formal analysis, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was carried out within the WATER MINING (Next generation water-smart management systems: large scale demonstrations for a circular economy and society) project. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869474.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.desal.2024.118213.

Data availability

Data will be made available on request.

References

[1] E. Ahmadi, B. McLellan, B. Mohammadi-Ivatloo, T. Tezuka, The Role of Renewable Energy Resources in Sustainability of Water Desalination as a Potential Fresh-Water Source: An Updated Review, Sustainability 12 (2020) 5233, https://doi.org/10.3390/su12135233.

[2] F.E. Ahmed, R. Hashaikeh, N. Hilal, Hybrid technologies: The future of energy efficient desalination – A review, Desalination 495 (2020) 114659, https://doi.org/10.1016/j.desal.2020.114659.

[3] S. Akhter, Key informants' interviews, in: M.R. Islam, N.A. Khan, R. Baikady (Eds.), Principles of Social Research Methodology, Springer, Singapore, 2022, pp. 389–404.

[4] A. Aliewi, E. El-Sayed, A. Akbar, K. Hadi, M. Al-Rashed, Evaluation of desalination and other strategic management options using multi-criteria decision analysis in Kuwait, Desalination 413 (2017) 40–51, https://doi.org/10.1016/j.desal.2017.03.006.

[7] Abdelmalek Belatoui, Hassiba Bouabessalam, Omar Rouane Hacene, Jose Antonio, de-la-Ossa-Carretero, Elena Martinez-Garcia, and Jose Luis Sanchez-Lizaso., Environmental Effects of Brine Discharge from Two Desalinations Plants in Algeria (South Western Mediterranean), Desalin. Water Treat. 76 (2017) 311–318, https://doi.org/10.5004/dwt.2017.20812.

[8] A. Bryman, R.g. Burgess, Analyzing Qualitative Data, New York: Routledge, London, 1994.

[10] G. Cipolletta, N. Lancioni, Ç. Akyol, A.L. Eusebi, F. Fatone, Brine treatment technologies towards minimum/zero liquid discharge and resource recovery: State of the art and techno-economic assessment, J. Environ. Manag. 300 (2021) 113681, https://doi.org/10.1016/j.jenvman.2021.113681.

[11] L. Domènech, H. March, D. Saurí, Degrowth initiatives in the urban water sector? A social multi-criteria evaluation of non-conventional water alternatives in Metropolitan Barcelona, J. Clean. Prod. 38 (2013) 44–55, https://doi.org/10.1016/j.jclepro.2011.09.020.

[12] M. Elimelech, W.A. Phillip, The Future of Seawater Desalination: Energy, Technology, and the Environment, Science 333 (2011) 712–717.

[13] Y. Fernández-Torquemada, J.L. Sánchez-Lizaso, J.M. González-Correa, Preliminary Results of the Monitoring of the Brine Discharge Produced by the SWRO Desalination Plant of Alicante (SE Spain), Desalination 182 (1–3) (2005) 395–402, https://doi.org/10.1016/j.desal.2005.03.023.

[14] R. Fornarelli, F. Shahnia, M. Anda, P.A. Bahri, G. Ho, Selecting an economically suitable and sustainable solution for a renewable energy-powered water desalination system: A rural Australian case study, Desalination 435 (2018) 128–139.

[15] G. Gamboa, Z. Kovacic, M. Di Masso, S. Mingorría, T. Gomiero, M. Rivera-Ferré, M. Giampietro, The Complexity of Food Systems: Defining Relevant Attributes and Indicators for the Evaluation of Food Supply Chains in Spain, Sustainability 8 (6) (2016) 515, https://doi.org/10.3390/su8060515.

[16] U.S. Geological Survey, Mineral commodity summaries 2020: U.S, Geological Survey (2020) 200, https://doi.org/10.3133/mcs2020.

[17] M. Giampietro, K. Mayumi, The Biofuel Delusion: The Fallacy of Large Scale Agro-Biofuels Production, Routledge, 2009.

[18] N. Heck, A. Paytan, D.C. Potts, B. Haddad, K.L. Petersen, Management priorities for seawater desalination plants in a marine protected area: A multi-criteria analysis, Mar. Policy 86 (2017) 64–71, https://doi.org/10.1016/j.marpol.2017.09.012.

[21] Y. Ibrahim, H.A. Arafat, T. Mezher, F. AlMarzooqi, An integrated framework for sustainability assessment of seawater desalination, Desalination 447 (2018) 1–17, https://doi.org/10.1016/j.desal.2018.08.019.

[22] Instituto Nacional de Estadísticas, INE, Survey on the use of water in the agricultural sector. National and by autonomous Comumunity results, 2000–2018 Series. Available online: https://www.ine.es/dyngs/INEbase/en/operacion.htm?c=Estadistica_C&cid=1254736176839&menu=resultados&idp=1254735976602, 2020.

[23] Instituto Nacional de Estadísticas,INE, Contabilidad Regional de España, Serie (2022) 2000–2021. Available at: https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736167628&menu=ultiDatos&idp=1254735576581.

[24] International Desalination Association – IDA, IDA Desalination & Reuse Handbook, 2021, pp. 2021–2022.

[26] Junta de Andalucía. 2015. Andalusian mediterranean basins water district. Management Plan 2015–2021. Available at: https://juntadeandalucia.es/medioambiente/site/portalweb/menuitem.7e1cf46ddf59bb227a9ebe205510e1 ca/?vgnextoid=4d01df1837fa1510VgnVCM2000000624e50aRCRD&vgnextchannel=953d4ae7a9aa1510VgnVCM2000000624e50aRCRD.

[28] U.K. Kesieme, N. Milne, H. Aral, C.Y. Cheng, M. Duke, Economic analysis of desalination technologies in the context of carbon pricing, and opportunities for membrane distillation, Desalination 323 (2013) 66–74, https://doi.org/10.1016/j.desal.2013.03.033.

[31] J. Kim, S. Hong, A novel single-pass reverse osmosis configuration for high-purity water production and low energy consumption in seawater desalination, Desalination 429 (2018) 142–154, https://doi.org/10.1016/j.desal.2017.12.026.

[32] J. Kim, K. Park, D.R. Yang, S. Hong, A comprehensive review of energy consumption of seawater reverse osmosis desalination plants, Appl. Energy 254 (2019) 113652, https://doi.org/10.1016/j.apenergy.2019.113652.

[33] N. Kress, Y. Gertner, E. Shoham-Frider, Seawater Quality at the Brine Discharge Site from Two Mega Size Seawater Reverse Osmosis Desalination Plants in Israel (Eastern Mediterranean), Water Res. 171 (2020) 115402, https://doi.org/10.1016/j.watres.2019.115402.

[34] R. Ktori, M. Palmeros-Parada, M. Rodriguez-Pascual, M.C.M. van Loosdrecht, D. Xevgenos, Designing for the future: A Value-Sensitive Approach to Integrated Desalination and Brine Treatment, TechRxiv (2024), https://doi.org/10.36227/techrxiv.170594775.55495325/v1.

[35] R. Ktori, M. Palmeros-Parada, M. Rodriguez-Pascual, M.C.M. van Loosdrecht, D. Xevgenos, Sustainability Assessment Framework for Integrated Desalination and Resource Recovery: A Participatory Approach. (2024), https://doi.org/10.2139/ssrn.4805181.

[36] T.K. Liu, J.A. Ye, H.Y. Sheu, Exploring the social acceptability for the desalination plant project: Perceptions from the stakeholders, Desalination 532 (2022) 115757, https://doi.org/10.1016/j.desal.2022.115757.

[37] M. Marini, C. Palomba, P. Rizzi, E. Casti, A. Marcia, M. Paderi, A multicriteria analysis method as decision-making tool for sustainable desalination: the Asinara island case study, Desalin. Water Treat. 61 (2017) 274–283, https://doi.org/10.5004/dwt.2016.11061.

[38] A. Marques-Postal, G. Benatti, M. Palmeros-Parada, L. Asveld, P. Osseweijer, J.M.F. J. Da Silveira, The Role of Participation in the Responsible Innovation Framework for Biofuels Projects: Can It Be Assessed? Sustainability 12 (2020) 10581 https://doi.org/10.3390/su122410581.

[40] M. Micari, A. Cipollina, A. Tamburini, M. Moser, V. Bertsch, G. Micale, Techno-economic analysis of integrated processes for the treatment and valorisation of neutral coal mine effluents, J. Clean. Prod. 270 (2020) 122472, https://doi.org/10.1016/j.jclepro.2020.122472.

[41] Ministerio de Agricultura, Pesca Y Alimentación, MAPA, Anuario de Estadística 2019, Available online: https://www.mapa.gob.es/estadistica/pags/anuario/2019/anuario/AE19.pdf, 2020.

[42] T.M. Missimer, Environmental issues in seawater reverse osmosis desalination: intakes and outfalls, Desalination 434 (2018) 198–215, https://doi.org/10.1016/j.desal.2017.07.012.

[43] C. Morgante, F. Vassallo, C. Cassaro, G. Virruso, D. Diamantidou, N. Van Linden, A. Trezzi, C. Xenogianni, R. Ktori, M. Rodriguez, G. Scelfo, S. Randazzo, A. Tamburini, A. Cipollina, G. Micale, D. Xevgenos, Pioneering minimum liquid discharge desalination: A pilot study in Lampedusa Island, Desalination 581 (2024) 117562, https://doi.org/10.1016/j.desal.2024.117562.

[44] H. Nassrullah, S.F. Anis, R. Hashaikeh, N. Hilal, Energy for desalination: A state-of-the-art review, Desalination 491 (2020) 114569, https://doi.org/10.1016/j.desal.2020.114569.

[46] Parada M. Palmeros, L. Asveld, P. Osseweijer, J.A. Posada, Setting the Design Space of Biorefineries through Sustainability Values, a Practical Approach, Biofuels Bioprod. Biorefin. 12 (1) (2018) 29–44, https://doi.org/10.1002/bbb.1819.

[47] Parada M. Palmeros, L. Asveld, P. Osseweijer, J.A. Posada, Integrating Value Considerations in the Decision Making for the Design of Biorefineries, Sci. Eng. Ethics 26 (2020) 2927–2955, https://doi.org/10.1007/s11948-020-00251-z.

[48] M. Palmeros-Parada, P. Kehrein, D. Xevgenos, L. Asveld, P. Osseweijer, Societal Values, Tensions and Uncertainties in Resource Recovery from Wastewaters, J. Environ. Manag. 319 (2022) 115759, https://doi.org/10.1016/j.jenvman.2022.115759.

[49] M. Palmeros-Parada, S. Randazzo, G. Gamboa, R. Ktori, B. Bouchaut, A. Cipolina, G. Micale, D. Xevgenos, Resource recovery from desalination, the case of small islands, Resour. Conserv. Recycl. 199 (2023) 107287, https://doi.org/10.1016/j.resconrec.2023.107287.

[50] A. Panagopoulos, K.J. Haralambous, Environmental impacts of desalination and brine treatment - Challenges and mitigation measures, Mar. Pollut. Bull. 161, Part B (2020) 111773, https://doi.org/10.1016/j.marpolbul.2020.111773.

[51] P. Paneque-Salgado, S. Corral-Quintana, Â. Guimarães-Pereira, L. del Moral Ituarte, B. Pedregal-Mateos, Participative multi-criteria analysis for the evaluation of water governance alternatives. A case in the Costa del Sol (Málaga), Ecol. Econ. 68 (4) (2009) 990–1005, https://doi.org/10.1016/j.ecolecon.2006.11.008.

[52] M. Papapetrou, A. Cipollina, U. La Commare, G. Micale, G. Zaragoza, G. Kosmadakis, Assessment of methodologies and data used to calculate desalination costs, Desalination 419 (2017) 8–19, https://doi.org/10.1016/j.desal.2017.05.038.

[53] E.J. Patel, Debating Desalination: Stakeholder Participation and Decision-Making in Southern California, Water Alternatives 16 (2) (2023) 509–540.

[54] G. Payne, J. Payne, Key concepts in social research, SAGE Publications, Ltd, 2004, https://doi.org/10.4135/9781849209397.

[55] A. Pereira, A. Turnes, E. Nogueira, Report on innovative CE business models & green financing for mobilizing investments, in: Deliverable 9.2 Water Mining Project, 2023.

[56] K.L. Petersen, N. Heck, B. G. Reguero, D. Potts, A. Hovagimian, A. Paytan, Biological and physical effects of brine discharge from the Carlsbad Desalination plant and implications for future desalination plant constructions, Water 11 (2) (2019) 208, https://doi.org/10.3390/w11020208.

[57] Red Eléctrica de España, Emisiones de CO_2 asociadas a la generación de electricidad en España, Available online: https://api.esios.ree.es/documents/580/download?locale=es, 2021.

[58] J.H. Rieger, Key informant, in: G. Ritzer (Ed.), The Blackwell Encyclopedia of Sociology, Blackwell Publishing, Pp, 2007, pp. 2457–2458.

[59] R. Riera, F. Tuya, E. Ramos, M. Rodríguez, O. Monterroso, Variability of macrofaunal assemblages on the surroundings of a brine disposal, Desalination 291 (2012) 94–100, https://doi.org/10.1016/j.desal.2012.02.003.

[60] Ruiz-Baena N., n.d. Calidad de agua para riego. Instituto de Investigación y Formación Agraria y Pesquera. Consejería de Agricultura y Pesca, Junta de Andalucía. Available online: https://www.juntadeandalucia.es/agriculturaypesca/ifapa/servifapa/registro-servifapa/ac16139a-ee2d-431a-bc75-27014a284840/download.

[62] A. Shahmansouri, C. Bellona, Nanofiltration technology in water treatment and reuse: applications and costs, Water Sci. Technol. 71 (3) (2015) 309–319, https://doi.org/10.2166/wst.2015.015.

[63] I. Sola, Y. Fernandez-Torquemada, A. Forcada, C. Valle, Y. Ruso, J.M. Gonzalez-Correa, Sustainable desalination: long-term monitoring of brine discharge in the marine environment, Mar. Pollut. Bull. 161 (Part B) (2020), https://doi.org/10.1016/j.marpolbul.2020.111813.

[64] I. Sola, C.A. Sáez, J.L. Sánchez-Lizaso, Evaluating environmental and socio-economic requirements for improving desalination development, J. Clean. Prod. 324 (2021) 129296, https://doi.org/10.1016/j.jclepro.2021.129296.

[65] I. Sutzkover-Gutman, D. Hasson, Feed water pretreatment for desalination plants, Desalination 264 (3) (2010) 289–296, https://doi.org/10.1016/j.desal.2010.07.014.

[66] T. Tong, M. Elimelech, The Global Rise of Zero Liquid Discharge for Wastewater Management: Drivers, Technologies, and Future Directions, Environ. Sci. Technol. 50 (13) (2016) 6846–6855, https://doi.org/10.1021/acs.est.6b01000.

[67] M. Trio, M.A. Ortuño, Panorama minero 2018–20, in: Instituto Geológico y Minero de España (IGME), 2020. Available online: https://web.igme.es/PanoramaMinero/Historico/2019/PANORAMA%20MINERO%202019.pdf.

[68] N. Voutchkov, Energy use for membrane seawater desalination – current status and trends, Desalination 431 (2018) 2–14, https://doi.org/10.1016/j.desal.2017.10.033.

[69] M.K. Wafi, N. Hussain, O. El-Sharief Abdalla, et al., Nanofiltration as a cost-saving desalination process, SN Appl. Sci. 1 (2019) 751, https://doi.org/10.1007/s42452-019-0775-y.

[70] J.E. Wood, J. Silverman, B. Galanti, Modelling the distributions of desalination brines from multiple sources along the Mediterranean coast of Israel, Water Res. 173 (2020) 115555, https://doi.org/10.1016/j.watres.2020.115555.

[71] D. Xevgenos, M. Marcou, V. Louca, E. Avramidi, G. Ioannou, M. Argyrou, P. Stavrou, M. Mortou, F.C. Küpper, Aspects of environmental impacts of seawater desalination: Cyprus as a case study, Desalin. Water Treat. 211 (2021) 15–30, https://doi.org/10.5004/dwt.2021.26916.

[72] D. Xevgenos, P. Michailidis, K. Dimopoulos, M. Krokida, M. Loizidou, Design of an innovative vacuum evaporator system for brine concentration assisted by software tool simulation, Desalin. Water Treat. 53 (12) (2015) 3407–3417, https://doi.org/10.1080/19443994.2014.948660.

[73] D. Xevgenos, K. Moustakas, D. Malamis, M. Loizidou, An overview on desalination & sustainability: renewable energy-driven desalination and brine management, Desalin. Water Treat. 57 (5) (2016) 2304–2314, https://doi.org/10.1080/19443994.2014.984927.

[74] D. Xevgenos, K.P. Tourkodimitri, M. Mortou, K. Mitko, D. Sapoutzi, D. Stroutza, M. Turek, M.C.M. van Loosdrecht, The concept of circular water value and its role in the design and implementation of circular desalination projects. The case of coal mines in Poland, Desalination 117501 (2024), https://doi.org/10.1016/J.DESAL.2024.117501.

[75] D. Xevgenos, A. Vidalis, K. Moustakas, D. Malamis, M. Loizidou, Sustainable management of brine effluent from desalination plants: the SOL-BRINE system, Desalin. Water Treat. 53 (12) (2015) 3151–3160, https://doi.org/10.1080/19443994.2014.933621.

[76] D. Zarzo, D. Prats, Desalination and energy consumption. What can we expect in the near future? Desalination 427 (2018) 1–9, https://doi.org/10.1016/j.desal.2017.10.046.

[77] X. Zhang, W. Zhao, Y. Zhang, V. Jegathesaan, A review of resource recovery from seawater desalination brine, Rev. Environ. Sci. Biotechnol. 20 (2021) 333–361 (2021), https://doi.org/10.1007/s11157-021-09570-4.

[78] N. Heck, A. Paytan, D.C. Potts, B. Haddad, Predictors of local support for a seawater desalination plant in a small coastal community, Environ. Sci. Policy (2016) 101–111, https://doi.org/10.1016/j.envsci.2016.08.009.

[79] N. Heck, K. Lykkebo Petersen, D.C. Potts, B. Haddad, A. Paytan, Predictors of coastal stakeholders' knowledge about seawater desalination impacts on marine eco- systems, Sci. Total Environ. 639 (2018) 785–792, https://doi.org/10.1016/j.scitotenv.2018.05.163.

[80] M. Palmeros-Parada, P. Osseweijer, Sustainable biorefineries, an analysis of practices for incorporating sustainability in biorefinery design, Ind. Crop. Prod. 106 (2017) 105–123, https://doi.org/10.1016/j.indcrop.2016.08.052.

[81] V. Cabello, A. Renner, M. Giampietro, Relational analysis of the resource nexus in arid land crop production, Adv. Water Resour. 130 (2019) 258–269, https://doi.org/10.1016/j.advwatres.2019.06.014.

[82] G. Gamboa, S. Mingorría, A. Scheidel, The meaning of poverty matters: trade-offs in poverty reduction programmes, Ecol. Econ. 169 (2020) 106450, https://doi.org/10.1016/j.ecolecon.2019.106450.

[83] G.C. Gallopín, Indicators and their use: Information for decision-making. Part One-Introduction, in: B. Moldan, S. Bilharz (Eds.), Sustainability Indicators. A Report on the Project on Indicators of Sustainable Development. SCOPE 58, Wiley, Chichester, 1997, pp. 13–27.

[84] P. Palenzuela, D.C. Alarcón-Padilla, G. Zaragoza, Large-scale solar desalination by combination with CSP: techno-economic analysis of different options for the Mediterranean Sea and the Arabian gulf, Desalination 366 (2015) 130–138, https://doi.org/10.1016/j.desal.2014.12.037.

[85] S. Lattermann, T. Höpner, Environmental impact and impact assessment of seawater desalination, Desalination 220 (2008) 1–15, https://doi.org/10.1016/j.desal.2007.03.009.

[86] Y. Fernández-Torquemada, A. Carratalá, J.L. Sánchez-Lizaso, Impact of brine on the marine environment and how it can be reduced, Desalination and Water Treatment 167 (2019) 27–37, https://doi.org/10.5004/dwt.2019.24615.

[87] Y. Fernández-Torquemada, J.M. Gónzalez-Correa, A. Loya, L.M. Ferrero, M. Díaz-Valdés, Dispersion of brine discharge from seawater reverse osmosis desalination plants, Desalin. Water Treat. 5 (1–3) (2009) 137–145, https://doi.org/10.5004/dwt.2009.576.

[88] H. March, D. Saurí, The end of scarcity? Water desalination as the new cornucopia for Mediterranean Spain, J. Hydrol. 519 (Part C) (2014) 2642–2651, https://doi.org/10.1016/j.jhydrol.2014.04.023.

[89] J. Davis, L.P. Nathan, Value Sensitive Design: Applications, Adaptations, and Critiques, in: J. van den Hoven, P. Vermaas, I. van de Poel (Eds.), Handbook of Ethics, Values, and Technological Design, Springer, Netherlands, Dordrecht, 2015, https://doi.org/10.1007/978-94-007-6970-0_3.

[90] B. Friedman, D.G. Hendry, A. Borning, A survey of value sensitive design methods, foundations and trends® in human–computer interaction 11 (2) (2011) 63–125, https://doi.org/10.1561/1100000015.